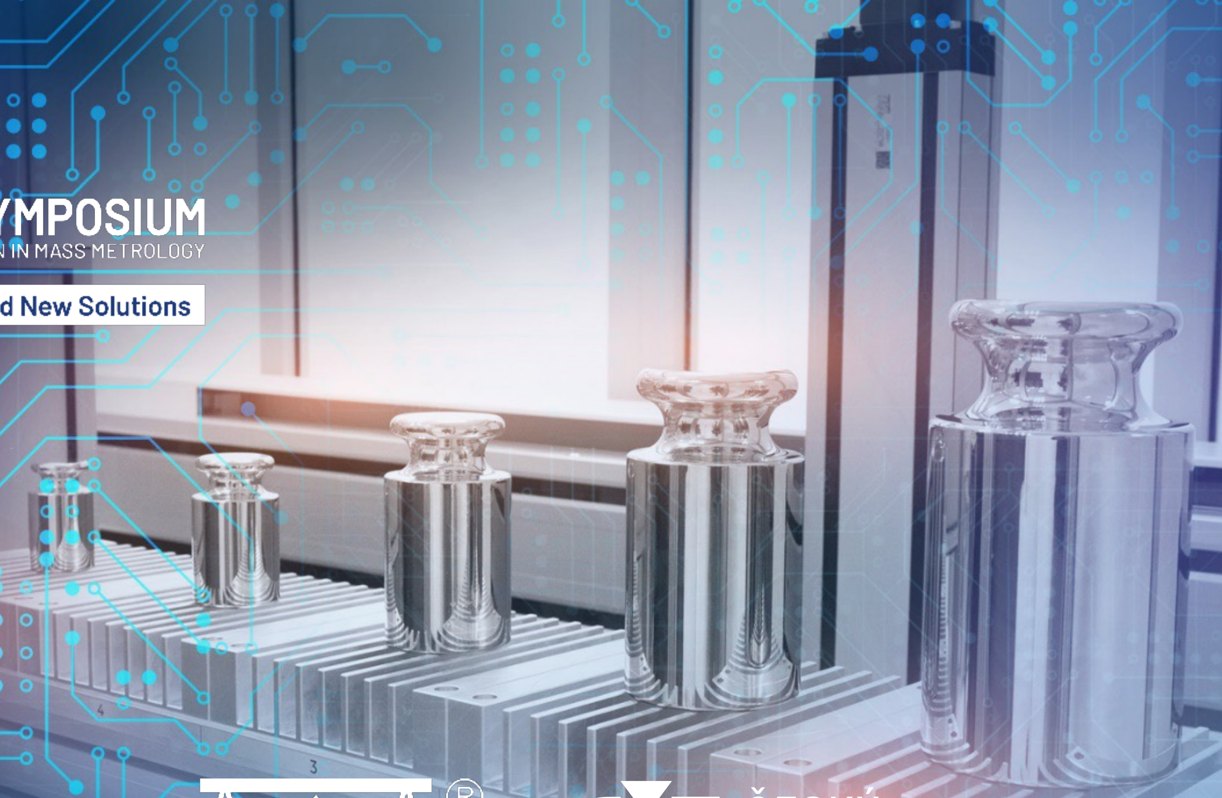
Pavel Klenovský, RNDr.

Director of Fundamental Metrology of CMI
Chairman of WELMEC

He received a diploma in Solid State Physics from the Masaryk University in Brno, Czechoslovakia in 1975 and a RNDr. degree in Quantum Physics from the same university in 1976. In 1977, he joined the Laboratory base in Brno of the state metrology organization (head of electricity lab) and in 1991, he became Deputy Director of new State Metrology Inspectorate aimed at legal metrology. In 1993, after the split of the Czechoslovak federation, he was appointed General Director of the newly established Czech Metrology Institute (CMI), national metrology institute of the Czech Republic in the area of fundamental and legal metrology. In 2021, he stepped down from this position and was appointed Deputy Director of Fundamental Metrology in CMI. He has been a long-term Czech delegate in international metrology organizations (EURAMET eV, WELMEC eV, OIML).

METROLOGY SYMPOSIUM
DIGITALIZATION AND AUTOMATION IN MASS METROLOGY

Third Edition: Future and New Solutions



RADWAG

ČESKÝ METROLOGICKÝ INSTITUT

Realization of the kilogram using the Planck constant

Jiří Tesař, Pavel Klenovský, CMI Czechia

Historical definitions of the kilogram

- After the Metre Convention, MC (French: Convention du Mètre) was launched it was decided at the 1st General Conference of Weights and Measures (CGPM) in 1889 to newly define the kilogram on the basis of **International Prototype (of Kilogram – IPK, Le Grand K**) as a platinum (90 %)-iridium (10%) alloy in custody of BIPM
- This prototype was intentionally manufactured in such a way to be, in value, as close as possible to the original definition as mass of 1 dm^3 of water

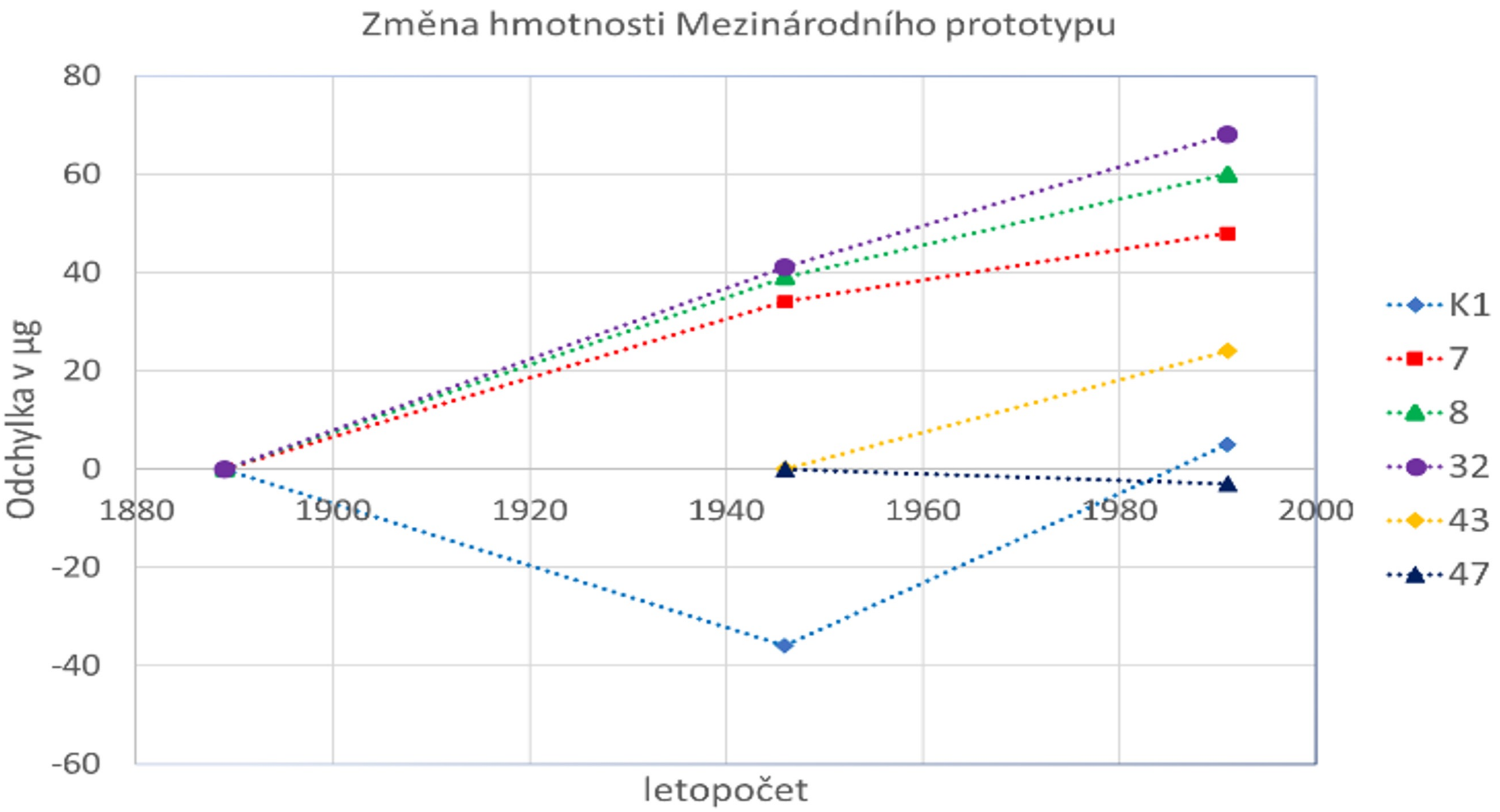
Source: BIPM

Historical definitions of the kilogram

- The following was manufactured and metrologically characterized in the course of time following that decision:
  - International Prototype of Kilogram (IPK)
  - 4 official copies for BIPM in 1889 (6 since 1946)
  - 35 copies for the current members of the Metre Convention at that time
- CGPM in 1901 decided that approximately every 40 up to 50 years a detailed comparison of IPK with its official copies would be organized (in fact: 1946, 1991 and 2014)

Source: BIPM

Comparison of the international prototype in 1990

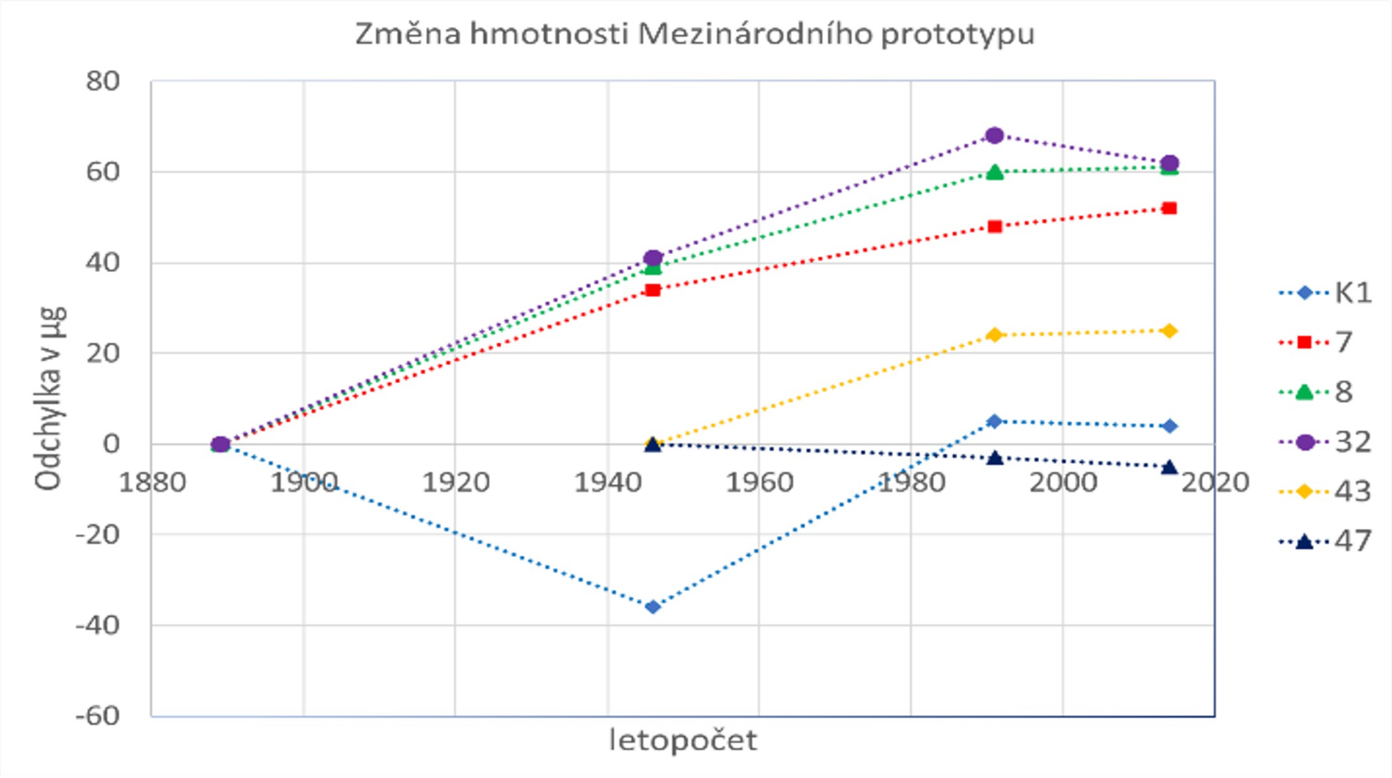


- On the basis of the comparison results until 1990 it was decided to repeat it already in 2014
- **The reason for the estimated drop in mass** of IPK was, in spite of a 15-year intensive research, **not found or explained** (Le Grand K seemed to be losing weight)

Comparison of the international prototype in 2014

- The results of the comparison of 2014 were quite surprising, to accelerate a redefinition of the unit of mass was a prevailing proposal for way forward

- This decision was approved by CGPM in 2014 (Resolution no. 1)

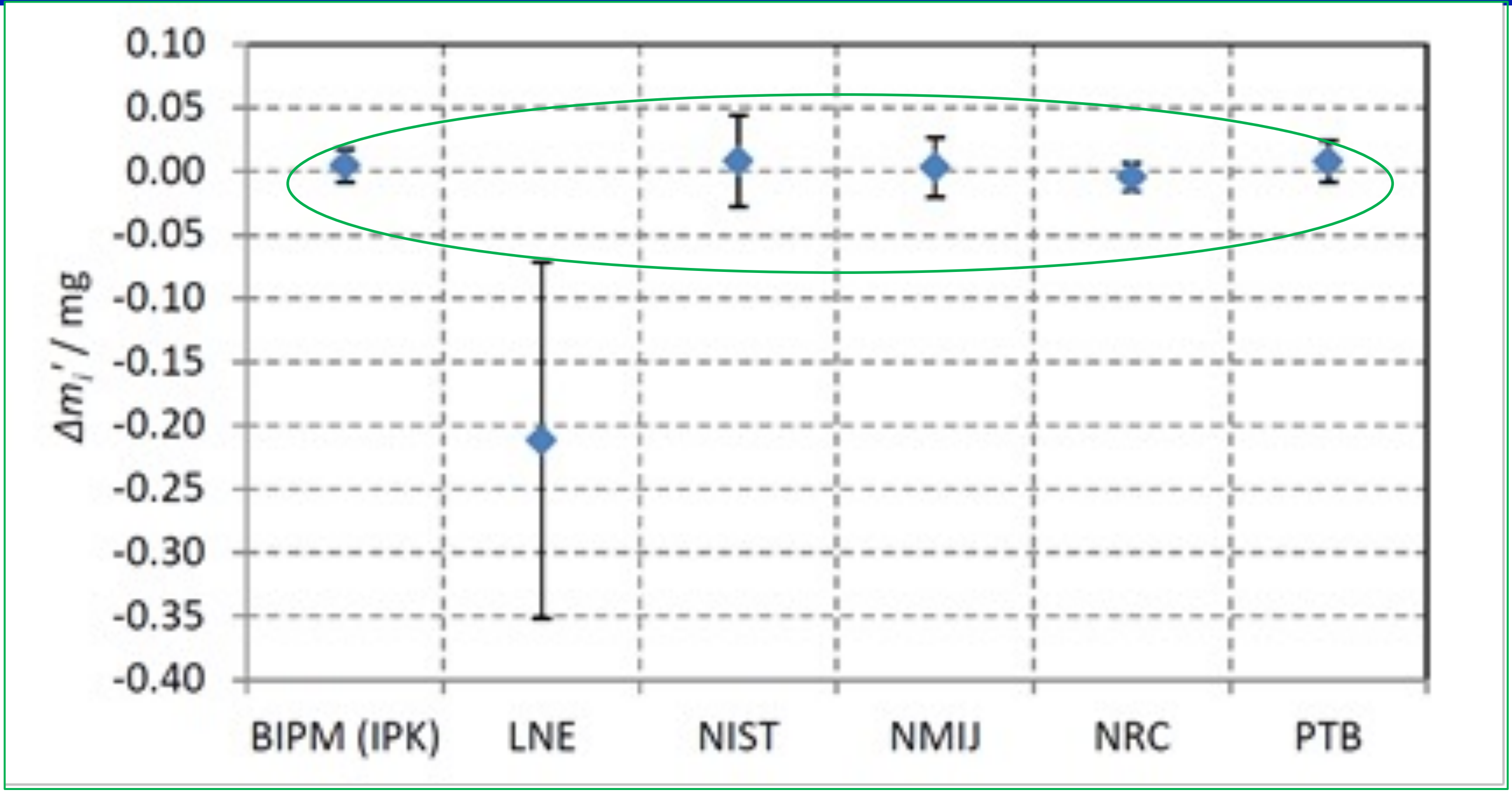


- A strict condition for the redefinition was laid down: **before a redefinition is approved a pilot comparison between primary realizations according to the new definition has to be <u>successfully</u> carried out**

Reasons for the redefinition

- Apart from problems with the value of the IPK itself the redefinition was accelerated also by pressure on the part of metrologists from the field of electricity
- Namely, the SI base unit of electrical current was at that time realized not according to its definition in SI but was based on primary standards of electrical voltage, resp. resistance based on Josephson, resp. von Klitzing hall quantum effects using **conventionally defined values** of the Josephson and von Klitzing constants (Resolution no. 2 of CGPM 1991)
- A direct relation of the unit ampere to the unit of mass (current balance) would never support precisions already achieved in electrical units by way of quantum standards („in 1991 electrical units were torn out from the SI system“) – it has been overcome by the redefinition in 2018

CCM Pilot study of the realization of kg - 2016



The results of the comparison made in 2016 showed **a very good agreement** between IPK and the realizations of the unit kilogram using the Kibble balance (NIST, NRC) and by the Avogadro experiment (PTB, NMIJ)

Therefore, the above mentioned condition for the redefinition of the kilogram has been fulfilled !

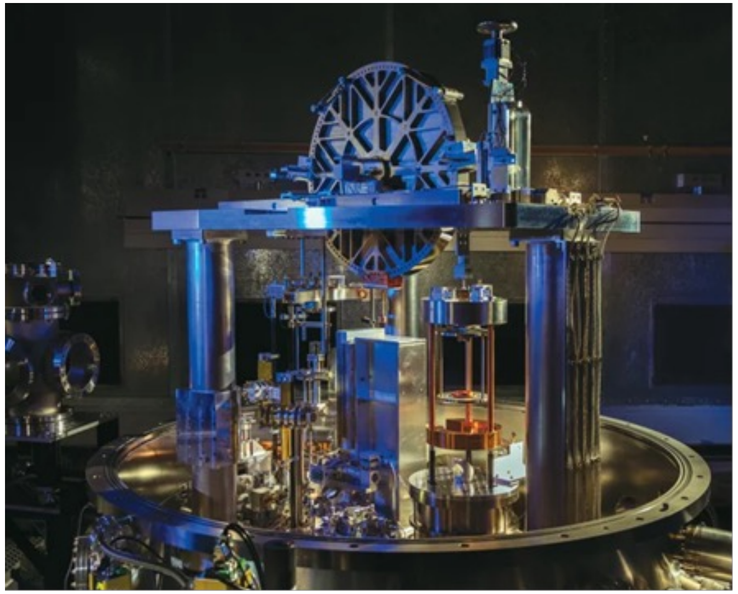
Redefinition of the kilogarm

- 26th General Conference of Weights and Measures (CGPM) in 2018 unanimously adopted the **redefinition of the unit kilogram** based on the Planck constant (in the form with an explicit definition of the constant):
- **Kilogram is defined by fixation of the numerical value of the Planck constant *h* equal to 6,626 070 15 × 10^{-34}, if expressed in the unit J.s which is equal to kg.m^{2}.s^{-1} where meter and second are defined using *c* and $\Delta \nu_{Cs}$**
- The redefinition of the kilogram was not effective immediately, it was delayed to May 20th, 2019 (the Day of Metrology)
- This new definition has been subsequently transposed to national Laws on Metrology of the member states, inclusive Czechia

Primary realizations of the kg after the redefinition

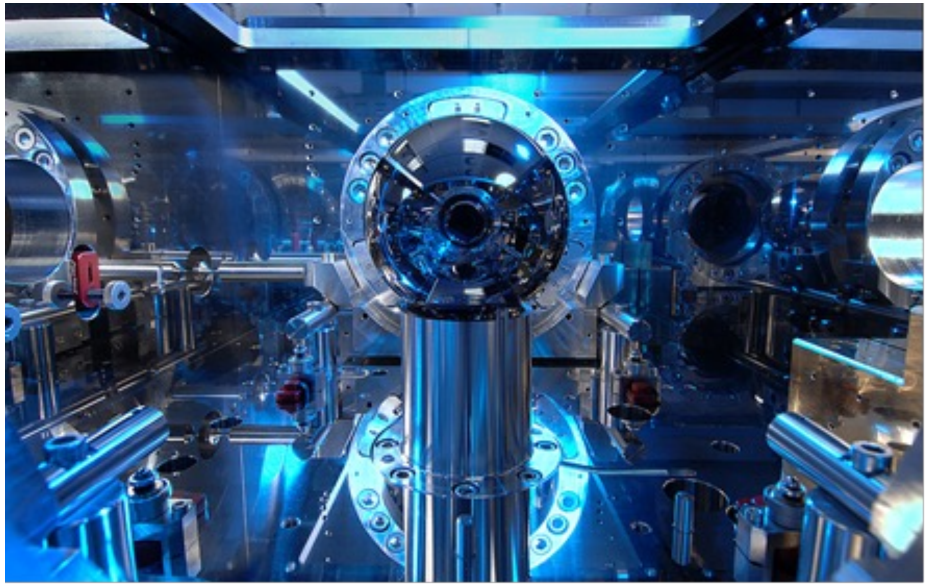
Currently, two physically completely different methods are used for primary realization of the unit of mass kilogram:

Kibble balance



Kibble balance in NIST USA

Avogadro experiment

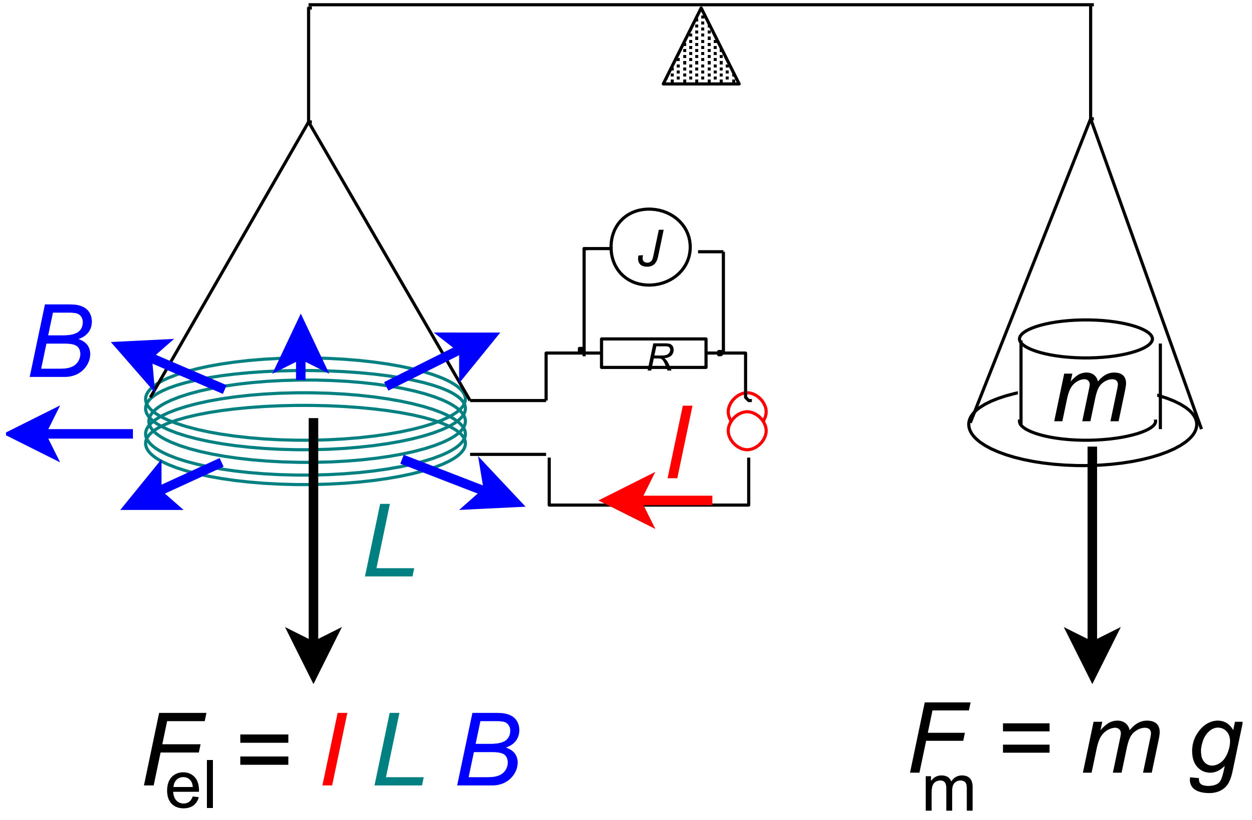


Avogadro experiment in PTB Germany

Based on the analysis of uncertainties both methods has the potential to achieve practically the same uncertainties of primary realization of the unit of mass ≤ 20 μg as required.

Kibble (watt) balance

Phase 1: static experiment



Weight of a test mass is compared with the force on a coil in a magnetic field.

$$mg = -I\frac{d\Phi}{dz}$$

In a radial magnetic field, this can be simplified to:

$$m\,g = I\,L\,B$$

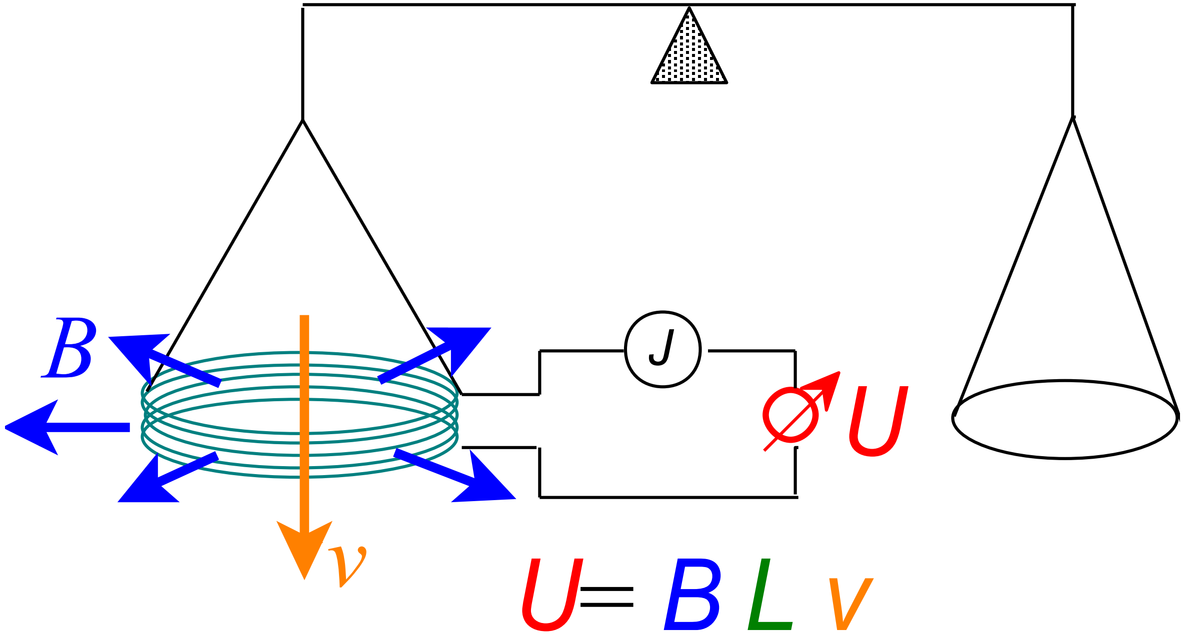
current (I)

coil wire length (L)

flux density (B)

Kibble (watt) balance

Phase 2: dynamic experiment



Coil is moved through the magnetic field and a voltage is induced.

$$U = -v \frac{d\Phi}{dz}$$

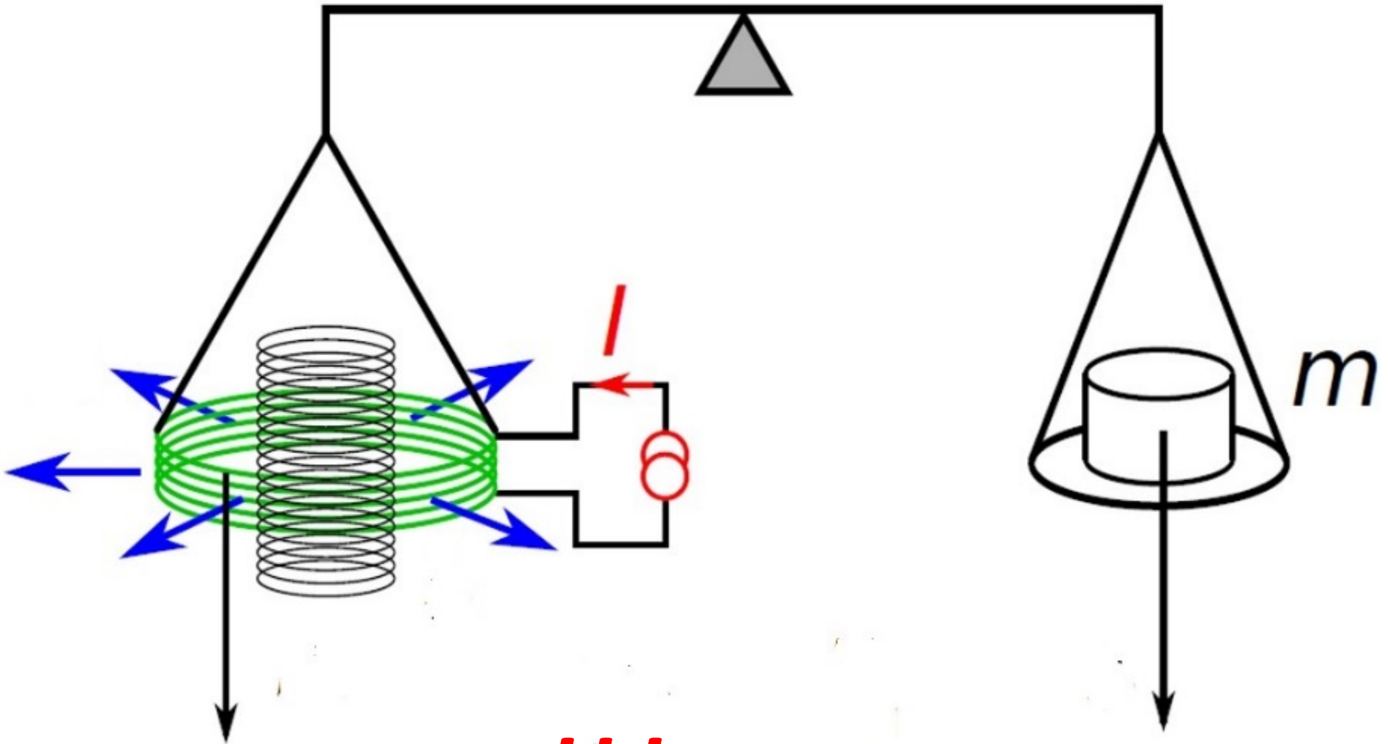
In a radial magnetic field, this can be simplified to:

$$U = B L v$$

ind. voltage (U), **flux density** (B), **coil wire length** (L), **velocity** (v)

Kibble (watt) balance

As a result electrical power is compared with a mechanical power – therefore, the original name „watt balance“ (electrical power is virtual !)



$$U\,I = m\,g\,v$$

electrical power → ← mechanical power

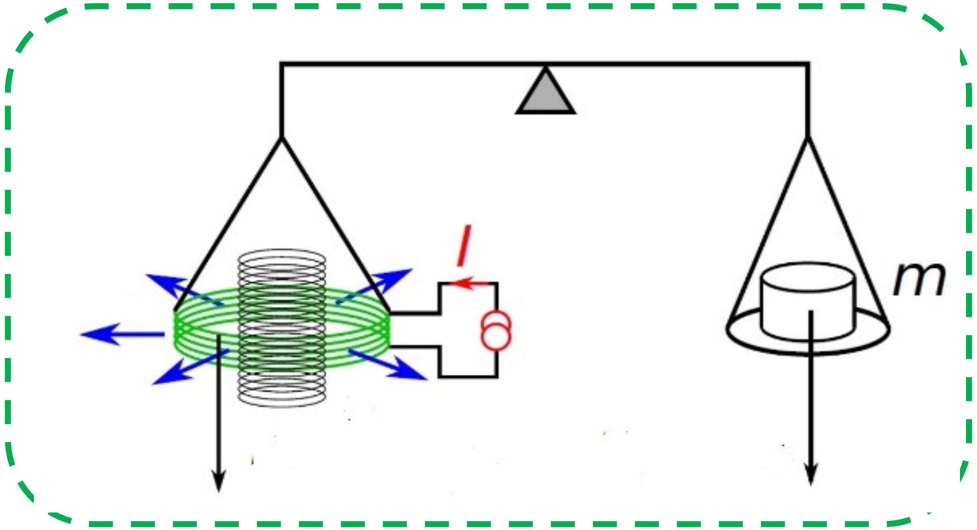
Kibble (watt) balance

$U \sim h/e$

quantum Josephson standard of DC voltage

$R \sim h/e2$

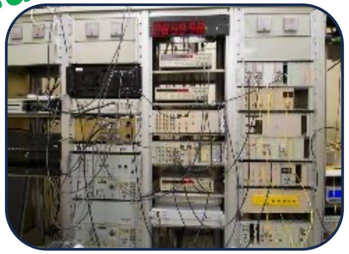
quantum Hall standard of electrical resistance



$$U\,I = m\,g\,v$$

$$m \sim h/4\,g\,v$$

high vaccuum standard



atomic clocks standard of time

absolute gravitometer standard of gr.acceleration

Michelson interferometer

Practical realization with the smallest theoretically achievable uncertainty ≤ 20 µg requires a combination of several primary standards in one experiment.

Avogadro experiment

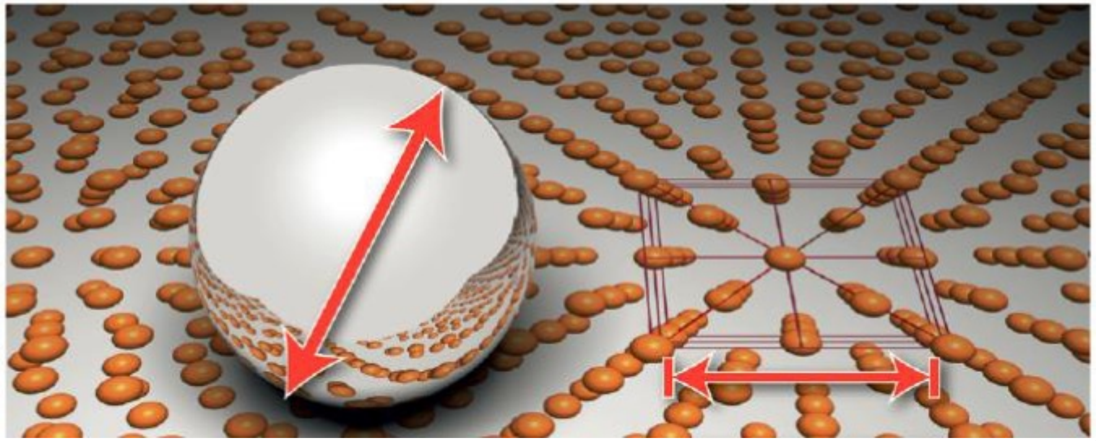
The Avogadro experiment is based on a simple principle where the mass of an object is determined from the number of its elementary particles and the mass of the single one – practical realization: silicon sphere

- manufacture of crystal lattice with minimum of imperfections
- manufacture of ideally monoisotopic crystal ^{28}Si
- chemically very stable surface

- homogenous surface layer
- to be manufactured with high precision

sphere diameter

sphere volume



silicon lattice constant

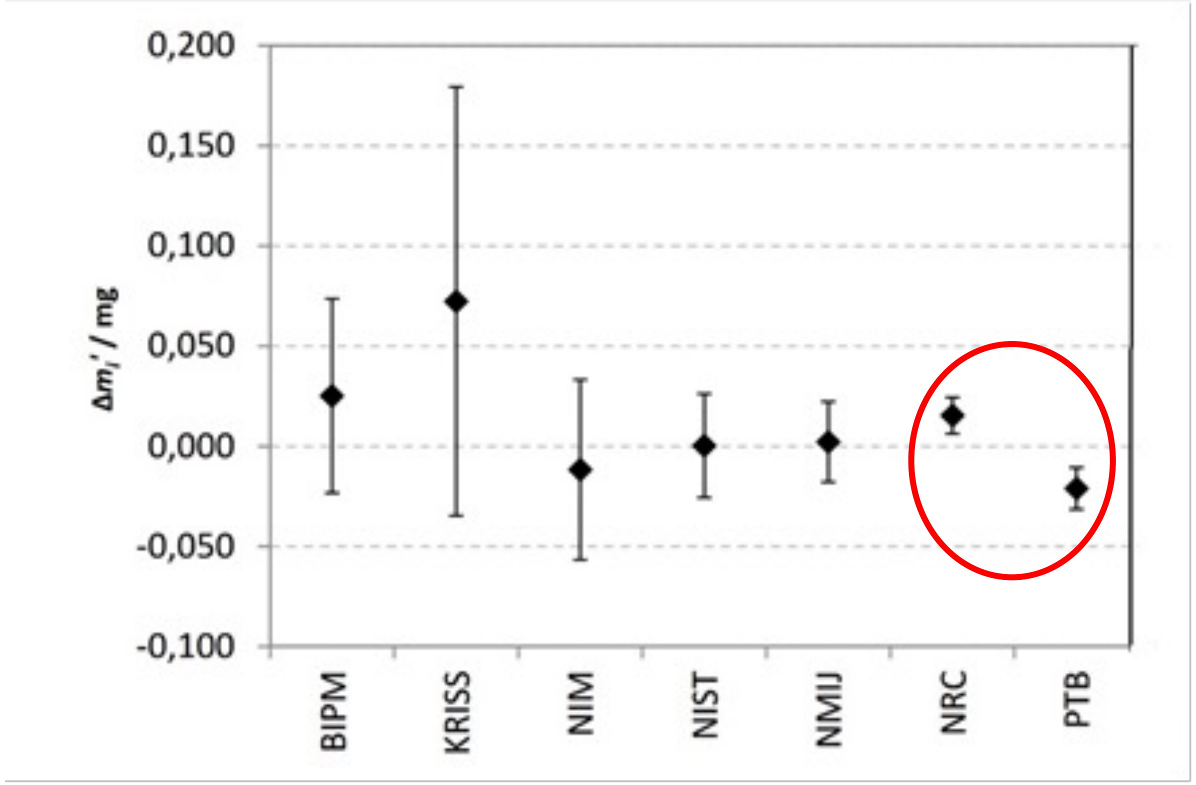
volume of one lattice cell of the crystal

number of atoms in the sphere

First key comparison after the redefinition - 2019

The results of the first key comparison of the kilogram raised concerns:

The agreement was considerably worse than in the case of the pilot study of 2016



- A disagreement between the most precise realizations of NRC and PTB was the main problem
- The uncertainties of all the others realizations of the kilogram are higher than required (and expected) 20 µg

Consensual value of the mass of the kilogram

- To overcome this problem Consultative Committee for Mass and Related Quantities (CCM) of CIPM has taken a „transitional“ measure – an introduction of a Consensual value of the mass of the kilogram (subsequently approved at CGPM 2022)
- Based on the results of the first key comparison in 2019 the Consensual value of the mass of the kilogram was set down as:

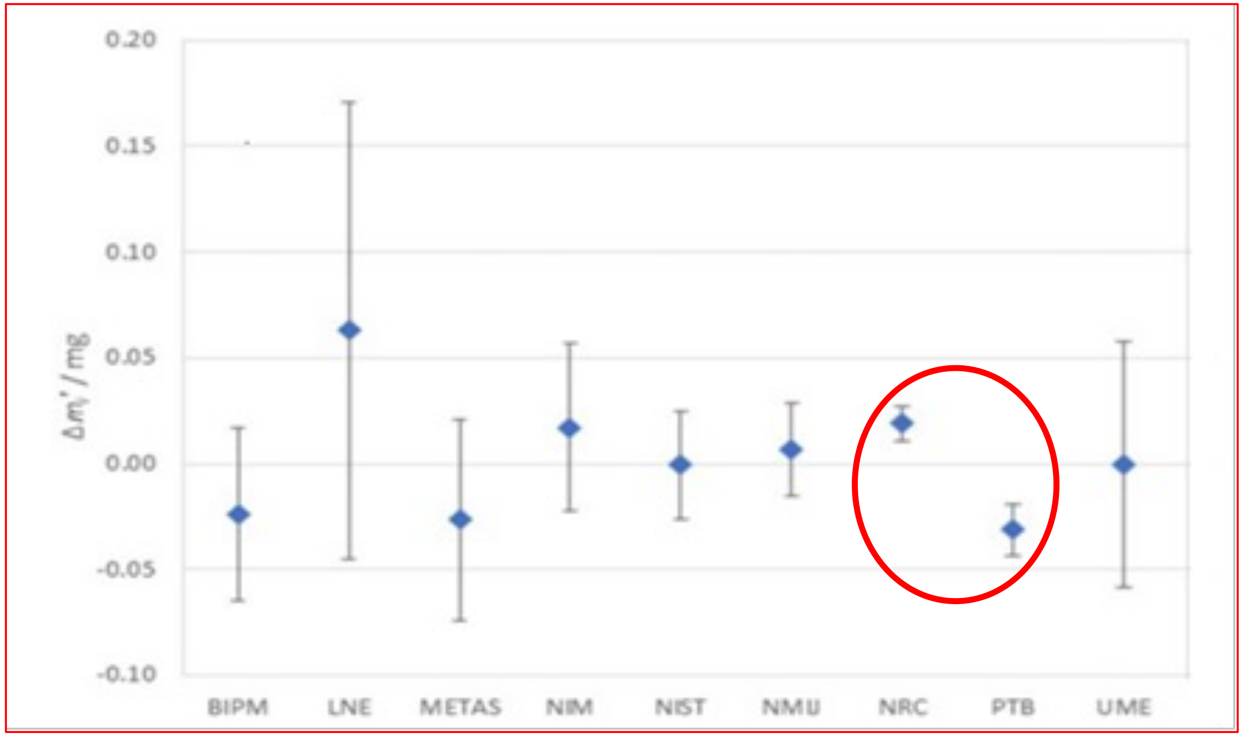
1 kg – 2 µg with the standard uncertainty of 20 µg

- This consensual value of the mass of the kilogram became effective on February 1st, 2021

Consensual value of the mass of the kilogram

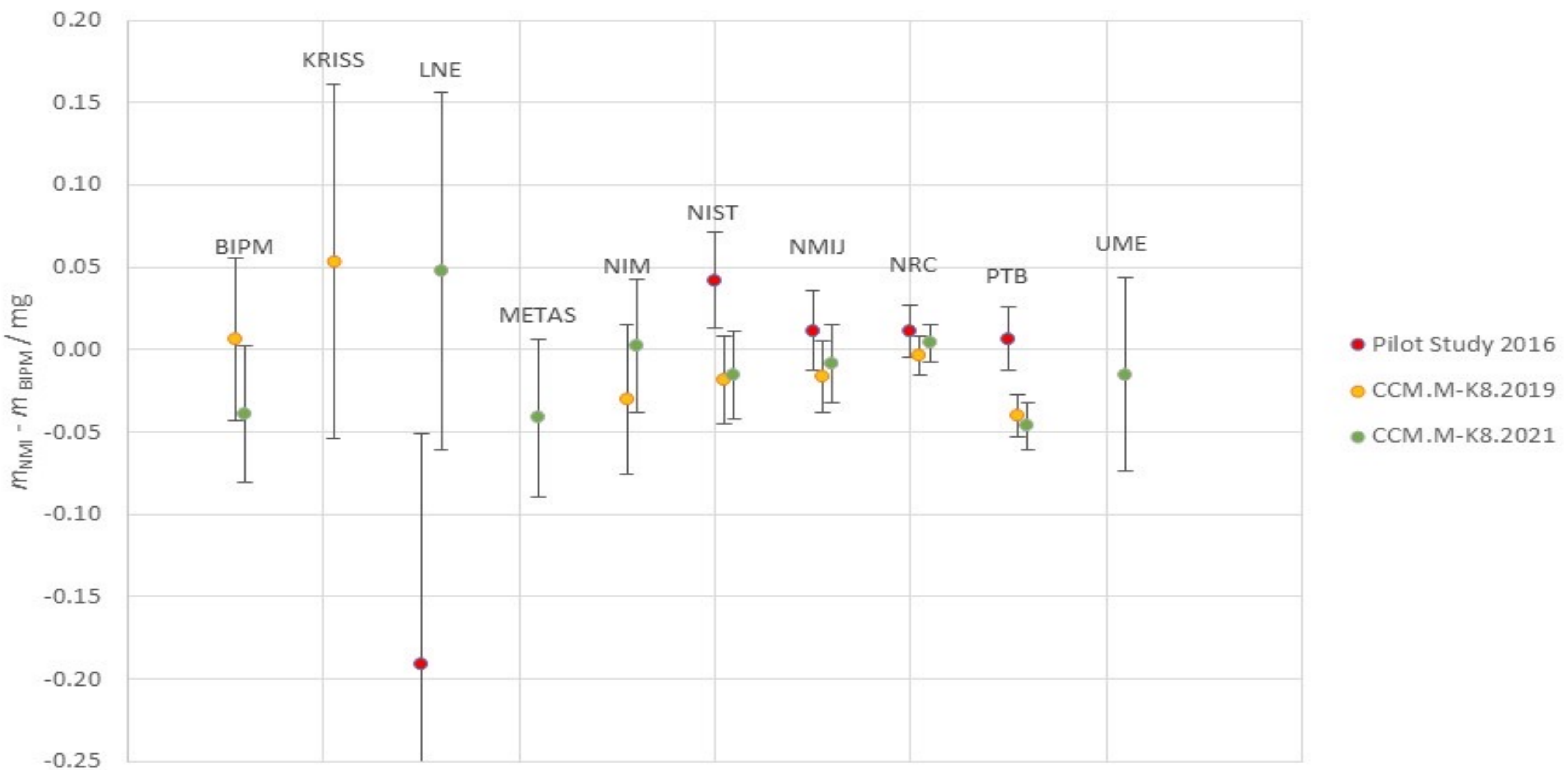
- **Traceability to the Planck constant realized in the „transitional“ period only through the Consensual value of the mass**
  - Currently realized only by way of calibrations at BIPM using the International prototype with the consensual value
- **Direct traceability to the Planck constant**
  - realizations through primary standards in individual NMIs
  - to be applicable after the results from sufficient number of primary realizations of the kilogram are in agreement with the Consensual value within the stated uncertainties

The 2nd key comparison after the redefinition - 2021



- The results confirmed **the mutual discrepancy of the two most precise realizations** using the Kibble balance and the Avogadro experiment
- The values of PTB and NRC were more apart from each other than in 2019
- The uncertainties of all the other realizations were again higher than the desirable 20 μg

Comparison of the pilot study and both key comparisons



Consensual value of the mass of the kilogram

- Based on the results of the key comparison of 2021 the Consultative Committee for Mass and Related Quantities (CCM) approved in February 2023 the new Consensual value of the mass of the kilogram:

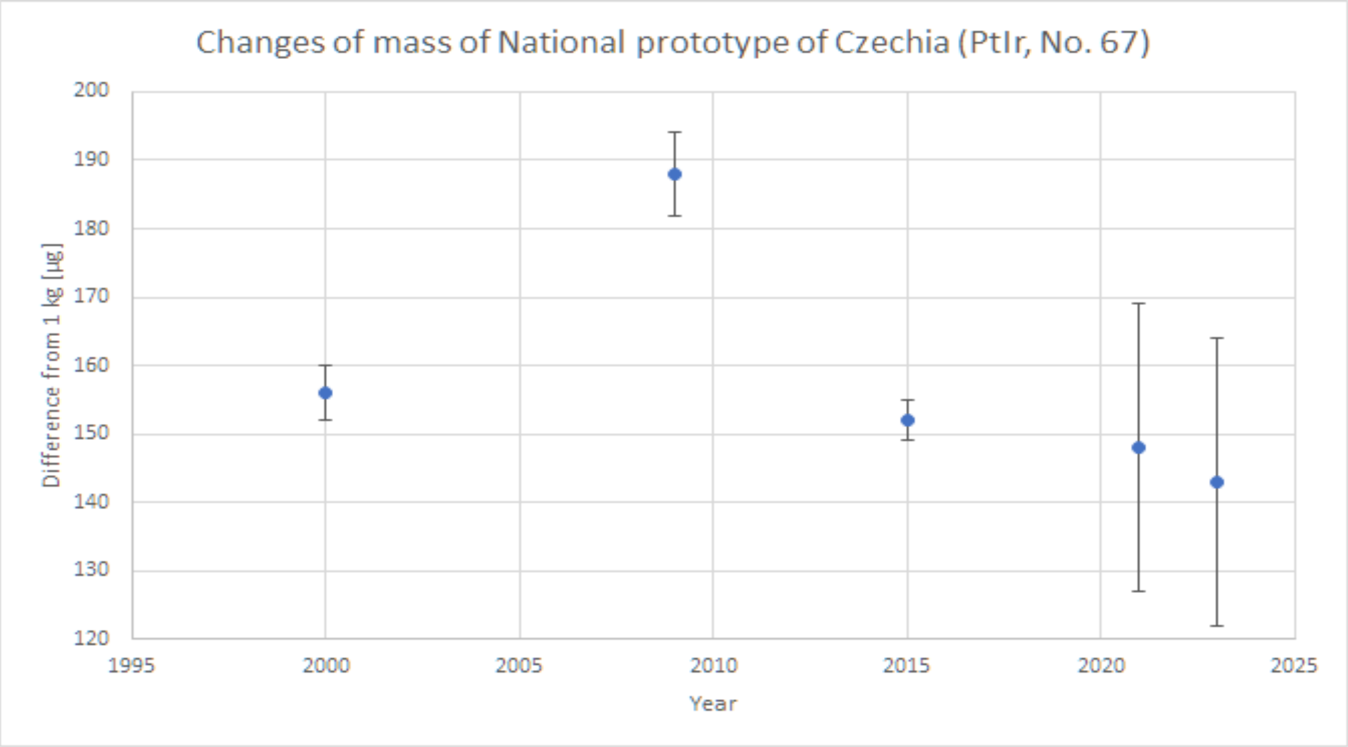
  1 kg – 7 µg with the standard uncertainty of 20 µg

- **New consensual value became effective on March 1st, 2023**
- Any change of the Consensual value in the near future cannot reasonably be expected

Consensual value of the mass of the kilogram

- The next key comparison of the realization of the kilogram has been postponed as late as to 2025
- **The reasons why a termination of the use of the Consensual value of mass in this decade is quite improbable are twofold:**
  - **disagreement (dispersion)** of the individual realized values of the unit of mass kilogram
  - too **high uncertainties** of the most realizations (globally only 2 realizations have uncertainties less than the specified target uncertainty of 20 µg)

Czech national standard of mass



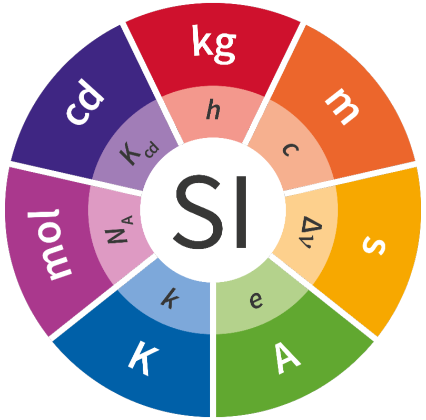
- Pictured is the development in time of the value of the Czech national standard – copy of IPK no. 67
- **The increased uncertainty of its value is a logical consequence of the introduction of the Consensual value**
- The 2009 value very well exemplifies problems caused by changes in mass of the IPK

Discussion of the impact of the redefinition

- The difficulties with the primary realization of the new definition of the unit of mass kilogram have been for a transitional period of time overcome by introducing of the Consensual value of mass of the kilogram = in effect, the International prototype keeps to be used for the dissemination of the unit of mass
- With some exceptions there are difficulties in obtaining uncertainties determined by theoretical evaluations
- The termination of the use of the Consensual value in this decade is, taken into account the available technologies and the results so far reached, rather improbable

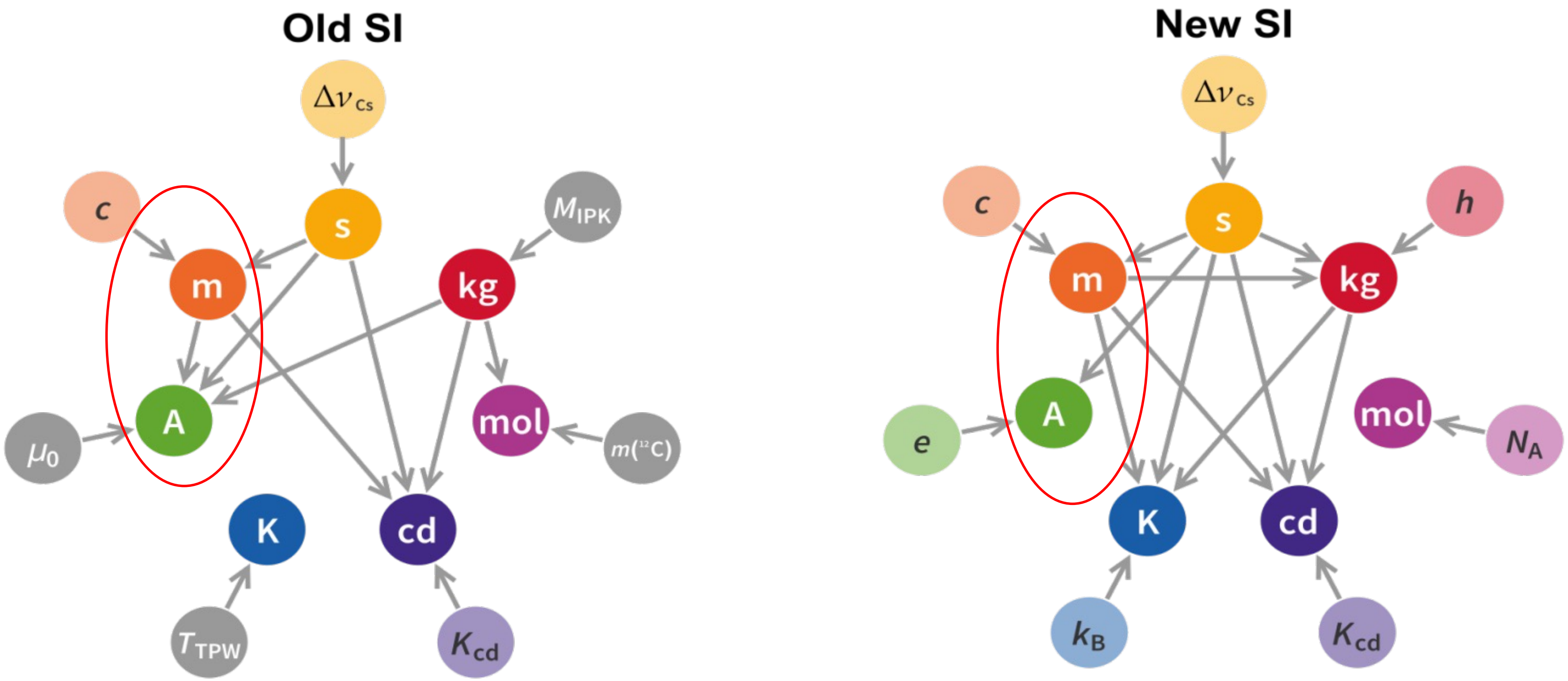
Discussion of the impact of the redefinition

- The use of the Consensual value of mass has no practical impact on accuracy and precision of weighing in industrial, trade or other applications (except for special scientific experiments)
- By redefinition, the conventional values used in primary realizations of the electrical units have been eliminated („the electrical units have returned to the womb of the SI“)
- It is technically possible to realize primary standards of the derived quantities (e.g. pressure) without traceability to the SI unit of mass



Electrical versus mass units

As the comparison of the old and new SI clearly shows, in new SI there is no direct connection between ampere and kilogram as in the old one which has enabled a full use of quantum primary standards in electricity supported by constants of nature and in this way to improve uncertainties in electricity



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